Published online January 3, 2006

Environmental and Production Consequences of Using Alum-Amended Poultry Litter as a Nutrient Source for Corn

Jason G. Warren,* Steven B. Phillips, Greg L. Mullins, Dale Keahey, and Chad J. Penn

ABSTRACT

Field trials were established to compare alum-treated poultry litter (ATPL), normal poultry litter (NPL), and triple superphosphate (TSP) as fertilizer sources for corn (*Zea mays* L.) when applied at rates based on current litter management strategies in Virginia. Trials were established in the Costal Plain and Piedmont physiographic regions near Painter and Orange, VA, respectively. Nitrogen-based applications of ATPL or NPL applied at rates estimated to supply 173 kg of plant-available nitrogen (PAN) ha^{-1} resulted in significantly lower grain yields than treatments receiving commercial fertilizer at the same rate in 2000 and 2001 at Painter. These decreases in grain yield at the N-based application rates were attributed to inadequate N availability, resulting from overestimates of PAN as demonstrated by tissue N concentrations. However, at Orange no treatment effects on grain yield were observed. Applications of ATPL did not affect Al concentrations in corn ear-leaves at either location. Exchangeable soil Al concentrations were most elevated in treatments receiving only NH_4NO_3 as an N source. At N-based application rates, the ATPL resulted in lower Mehlich 1–extractable P (M1-P) and water-extractable soil phosphorus (H_2O-P) concentrations compared to the application of NPL. A portion of this reduction could be attributed to lower rates of P applied in the N-based ATPL treatments. Runoff collected from treatments which received ATPL 2 d before conducting rainfall simulations contained 61 to 71% less dissolved reactive phosphorus (DRP) than treatments receiving NPL. These results show that ATPL may be used as a nutrient source for corn production without significant management alterations. Alum-treated poultry litter can also reduce the environmental impact of litter applications, primarily through minimizing the P status of soils receiving long-term applications of litter and reductions in runoff DRP losses shortly after application.

Historically, poultry (*Gallus gallus domesticus*) litter has been utilized as a fertilizer source for agricultural fields. Because N is often the most limiting nutrient for crop production, litter has typically been applied at rates to supply adequate amounts of N for crop production. The N to P ratio found in poultry litter ranges from 0.6 to 1.0 (Evanylo and Mullins, 2000), yet the ratio of N removed to P removed by crops grown in Virginia ranges from 2.0 in cotton (*Gossypium hirsutum* L.) to 9.0 in peanut (*Arachis hypogaea* L.) (Donohue, 2000). Therefore, long-term applications of poultry litter result in elevated soil test P levels (Kingery et al., 1994; Sharpley et al., 1993). In fact, many soils found near areas of high poultry production in Virginia, which have historically received litter applications, currently have high to very high M1-P levels (>28 mg P kg^{-1} soil) (Brosius et al., 2000).

Increases in soil test P due to poultry litter applications can correspond to an increase in soluble P concentrations in surface water runoff (Sharpley, 1995). This increase can lead to P loading of surface water bodies. Phosphorus is the limiting nutrient in most aquatic systems; therefore, the addition of nonpoint-source P pollution from agricultural lands can be a contributor to eutrophication of sensitive water bodies (Pote et al., 1996). Thus, major efforts are being made by policymakers to curb nonpoint-source P pollution in surface water bodies. For example, Virginia's Poultry Waste Management Act of 1999 requires poultry producers to have P-based nutrient management plans, which limit poultry litter application rates to crop requirements of P, based on soil test recommendations or crop removal of P, whichever is greater. The Delaware Nutrient Management Act of 1999 mandates that P applications to soils containing high P concentrations be no greater than the estimated 3-yr crop removal (Sims, 1999). Maryland's Water Quality Improvement Act of 1998 also requires producers to adopt P-based nutrient management plans (Simpson, 1998). Because many soils located relatively near poultry production operations already contain high to very high levels of soil test P, litter applications will most often be limited to rates equal to crop P removal. This limitation results in a dramatic increase in the land base needed for the utilization of poultry litter produced as well as increased costs associated with transporting litter away from poultry production facilities. It also increases the needs for supplemental commercial N fertilizer to fulfill the N requirements for crops grown on fields treated with poultry litter.

In addition to decreasing application rates to reduce soil P loading, other management options are being evaluated to reduce water quality impacts of using poultry litter as a nutrient source. One potential management practice for reducing the solubility of P in poultry litter is

J.G. Warren, S.B. Phillips, and D. Keahey, Eastern Shore Agricultural Research and Extension Center, Virginia Polytechnic Institute and State University, 33446 Research Drive, Painter, VA 23420; G.L. Mullins, New Mexico State University, Department of Agronomy and Horticulture, Room 127N, Skeen Hall, Las Cruces, NM 88003; C.J. Penn, USDA/ARS Pasture Systems and Watershed Management Research Unit, 3702 Curtain Road, University Park, PA 16802. Received 9 Nov. 2004. *Corresponding author (jawarre1@vt.edu).

Published in J. Environ. Qual. 35:172–183 (2006).
Technical Reports: Waste Management
doi:10.2134/jeq2004.0418

Abbreviations: ATPL, alum-treated poultry litter; CR, phosphorus application rate of 24 kg P ha^{-1}; 3CR, phosphorus application rate of 73 kg P ha^{-1}, applied once before planting in 2000; DRP, dissolved reactive phosphorus; H_2O-P, water-extractable soil phosphorus; M1-P, Mehlich 1–extractable soil phosphorus; NBAL, phosphorus application rate based on the carrier phosphorus in alum-treated poultry litter applied to supply 173 kg PAN ha^{-1}; NBNL, phosphorus application rate based on the carrier phosphorus in normal poultry litter applied to supply 173 kg PAN ha^{-1}; NPL, normal poultry litter without alum additions; PAN, plant-available nitrogen; TSP, triple superphosphate fertilizer.

the use of chemical amendments. Many Ca, Al, and Fe containing compounds such as alum $[Al_2(SO_4)_3 \cdot 16H_2O]$ and ferrous sulfate ($FeSO_4 \cdot 7H_2O$) (Shreve et al., 1996), sodium aluminate ($Na_2Al_2O_4$), quicklime (CaO), slaked lime $[Ca(OH)_2]$, calcitic limestone ($CaCO_3$), dolomitic limestone $[CaMg(CO_3)]$, gypsum ($CaSO_4 \cdot 2H_2O$), ferrous chloride ($FeCl_2 \cdot 4H_2O$), ferric chloride ($FeCl_3$), and ferric sulfate $[Fe_2(SO_4)_3 \cdot 2H_2O]$ (Moore and Miller, 1994) have been evaluated for their effectiveness in reducing soluble P in poultry litter. Of these amendments, alum has been shown to be an economically viable option for reducing the solubility of P in poultry litter (Moore et al., 1999) and is beginning to be used by producers. In a farm-scale study utilizing 194 poultry houses, half of which received alum additions, Sims and Luka-McCafferty (2002) found alum-treated poultry litter (ATPL) to contain 73% lower water-soluble P in litter compared to normal poultry litter (NPL). In a pen trial, Miles et al. (2003) found that the use of alum resulted in as much as a 60% reduction in water-soluble P found in litter depending on dietary formulation. These reductions in water-soluble P can be attributed to the adsorption of P to amorphous aluminum hydroxides which form in poultry litter after the addition of alum (Peak et al., 2002).

In addition to reduced P solubility, alum, when applied to the floor of production houses before the addition of each flock of birds, reduces NH_3 volatilization from poultry litter (Moore et al., 1995). This decrease in NH_3 volatilization results in an increase in the N content of the litter. Therefore, the value of the litter as an N source and its N to P ratio may be increased.

The use of ATPL in field trials has yielded results that demonstrate its effectiveness in minimizing P availability. Shreve et al. (1995) found that when applied to tall fescue (*Festuca arundinacea* Schreb.), the reduced concentration of water-soluble P in ATPL resulted in an 87% reduction in the concentration of dissolved reactive phosphorus (DRP) in runoff compared to plots receiving the same amount of NPL. Moore et al. (1999) demonstrated that three annual applications of ATPL to tall fescue resulted in lower H_2O-P and Mehlich 3–extractable P compared to NPL, when both were applied at rates of 2.24, 4.49, 6.73, and 8.98 Mg litter ha^{-1}. At the highest rate of 8.98 Mg litter ha^{-1}, H_2O-P increased to approximately 40 mg P kg^{-1} in treatments receiving NPL compared to approximately 10 mg P kg^{-1} in the control treatment receiving no P fertilizer. In comparison, H_2O-P in the treatment receiving the corresponding ATPL rate was approximately 15 mg P kg^{-1}, which was not significantly different from that found in the control treatment receiving no P fertilizer. The addition of ATPL at the 8.98 Mg ha^{-1} rate significantly increased Mehlich 3–extractable P compared to the control treatment receiving no P fertilizer, but was still nearly one-half the concentration found in the treatment receiving the same rate of NPL.

Additional field research has found that the treatment of poultry litter with alum has additional beneficial effects on surface runoff water quality. Specifically, Moore et al. (1998) found that the treatment of poultry litter with alum significantly reduced runoff concentrations of arsenic, copper, iron, and zinc from fescue pasture compared to NPL applications. These decreased metal concentrations were associated with decreased soluble organic carbon concentrations found in runoff collected from treatments receiving ATPL. Similarly, Nichols et al. (1997) found that applications of ATPL resulted in 42% lower concentrations of 17β-estradiol, an estrogen hormone, compared to NPL when applied on an equal dry weight basis.

Currently, limited field research data are available for the evaluation of ATPL as a nutrient source for crop production. As mentioned, Shreve et al. (1995) applied equivalent amounts of ATPL and NPL to tall fescue and found that applications of ATPL resulted in a 28% increase in total forage yield compared to NPL. Because litter sources were applied on an equal weight basis these increased yields were attributed to the higher N concentrations in ATPL resulting from decreased ammonia volatilization as reported by Moore et al. (1995). In the study conducted by Moore et al. (1995), NH_4–N concentrations found in poultry litter 42 d after the addition of 130 g of alum kg^{-1} were increased from 3.3 g N kg^{-1} in the control to as much as 11.2 g N kg^{-1} in the ATPL. Assuming the NH_4–N concentrations in litter used by Shreve et al. (1995) were similar to those reported by Moore et al. (1995), the NPL and ATPL applied at the rates used by Shreve et al. (1995) would have supplied approximately 37 and 125 kg NH_4–N ha^{-1}, respectively. This adequately explains the increased forage yields resulting from the use of ATPL.

Currently, no data are available in the literature where ATPL has been evaluated as a nutrient source for field crops such as corn. Specifically, no data are available evaluating ATPL and NPL applied at equivalent plant-available N and/or equal P rates. The possibility of increased exchangeable Al in soils treated with ATPL has received minor attention (Moore et al., 1999); however, the effect of ATPL applications on the P status of cultivated soils has not yet been evaluated. Because of decreased vegetative cover in a cultivated system compared to pasture systems, greater concentrations of total P loss may be expected in runoff from cultivated systems due to a higher potential for losses of litter particles and sediment (Sharpley et al., 1992). Of this P lost to runoff in cultivated systems, a smaller percentage is expected to be in soluble forms compared to P lost from pasture systems (Edwards and Daniel, 1993). These effects could impact the value of alum treatment as an option in reducing P losses. Therefore, it is important to evaluate alum treatment of poultry litter as a management practice to reduce P runoff from cultivated cropping systems.

The objective of this study was to evaluate production and environmental impacts of using ATPL as a nutrient source for corn production in accordance with current litter management strategies. The response of corn yield and elemental plant tissue concentrations to application of ATPL was evaluated. Also, the environmental impact of using ATPL was assessed through evaluation of changes in soil P status, soil exchangeable

Table 1. Three-year average total elemental composition of the alum-treated poultry litter (ATPL) and normal poultry litter (NPL) corrected to a dry weight.

Element	ATPL Value	ATPL CV†	NPL Value	NPL CV†
	mg kg^{-1}			
NH_4–N	17094	0.19	10625	0.11
Total N	54651	0.05	44501	0.05
P	16712	0.18	20150	0.10
K	28869	0.09	32004	0.08
Ca	19722	0.34	20529	0.32
Mg	8700	0.29	7808	0.18
S	24578	0.18	6861	0.03
Zn	558	0.07	545	0.07
Cu	694	0.38	798	0.06
Mn	694	0.08	669	0.06
Na	9126	0.12	10006	0.09
Al	8563	0.13	1221	0.13
Al to P ratio	0.51		0.06	

† Coefficient of variation for annual analysis of stockpiled litter.

Al content, and soil pH resulting from applications of ATPL. In addition simulated rainfall experiments were conducted to evaluate the effects of using ATPL on P runoff concentrations.

MATERIALS AND METHODS

Small plot field experiments were conducted at Virginia Tech's Northern Piedmont and Eastern Shore Agricultural Research & Extension Centers in Orange and Painter, VA, respectively, from 2000 through 2003. Field corn ('Pioneer 31G20') was planted at a rate of 55 600 kernels ha^{-1} in 0.91-m rows. Plots were six rows wide and 6.1 m long. The experimental area at Painter was on a Bojac sandy loam (coarse-loamy, mixed, semiactive, thermic Typic Hapludult). The experimental area at Orange was on a Davidson loam (fine, kaolinitic, thermic Rhodic Kandiudult).

Poultry Litter

Poultry litter used in the study was collected from two poultry houses included in the study presented by Sims and Luka-McCafferty (2002). One of the houses received alum at an approximate rate of 0.09 kg per bird before the introduction of each flock. The second house received no alum additions. Litter was collected at the end of a grow-out and transported to the research stations and stored in barrels until application. The average elemental compositions of the litters are presented in Table 1. The analyses were conducted by the University of Maryland Soil Testing Laboratory for the 2000 and 2001 growing seasons and by the Agricultural Service Laboratory, Clemson University, for the 2002 growing season.

Field Studies

Treatments consisted of triple superphosphate (TSP), ATPL, and NPL applied at four different phosphorus rates (Table 2). In addition to a no-phosphorus control treatment, phosphorus rates were based on: (i) applying NPL at rates to meet the nitrogen needs of the crop (NBNL); (ii) applying ATPL at rates to meet the nitrogen needs of the crop (NBAL); (iii) annual estimated crop removal of phosphorus (CR); and (iv) estimated three-year crop removal of phosphorus (3CR). The 3CR treatments were applied before planting only in the 2000 crop-year and supplemental N was applied in 2001 and 2002 to these treatments. This resulted in a total of 11 treatments, which were arranged in a randomized complete block design with four replications per treatment. This treatment structure was selected to evaluate ATPL under currently recommended or required nutrient management strategies employed in Virginia. At Painter, the control treatment did not receive any N fertilizer in 2002, which was done to evaluate the N response in the other treatments.

All plots were supplied with sufficient N for estimated corn grain yields of 8.8 Mg ha^{-1} (equivalent to 173 kg PAN ha^{-1}, assuming a requirement of 19.7 kg N Mg^{-1} of corn grain yield) (Evanylo and Alley, 1998) (Table 2). The availability of N in the NPL and ATPL was estimated using guidelines developed by the Virginia Department of Conservation and Recreation (1995). These guidelines assume that 90% of the NH_4–N and 60% of the organic N is available as plant-available nitrogen (PAN) for crop uptake in the year of application when litter is incorporated immediately after application. Phosphorus sources and supplemental N fertilizer were pre-plant broadcast-applied and incorporated immediately before planting. Because soil test K levels were below optimum, supplemental K fertilizer was applied at Orange to all treatments to supply 112, 67, and 67 kg K_2O ha^{-1} in 2000, 2001, and 2002, respectively. No supplemental potassium fertilizer was applied at Painter.

Corn grain yields were determined at maturity by harvesting the full length of the two center rows from each plot using a plot combine at Painter and by hand harvesting at Orange. Corn grain was weighed and subsampled by plot for moisture determination and elemental analysis. Corn grain yields are reported at a moisture content of 0.155 g kg^{-1}. Composite corn ear-leaf samples were collected at mid-silk from Rows 2 and 5 in each plot. Ear-leaf samples were not collected

Table 2. Three-year average litter application rates and corresponding P, plant-available nitrogen (PAN), NH_4NO_3–N, total PAN, and total N application rates resulting from each treatment combination.

P source	Rate†	Litter applied	P rate	PAN‡ applied as litter	Total N applied	NH_4NO_3–N applied	Total PAN‡ applied
		Mg ha^{-1}	kg ha^{-1}				
Control	–	0.0	0	0	173	173	173
Normal litter	NBNL	5.8	116	173	257	0	173
Triple super phosphate	NBNL	0.0	116	0	173	173	173
Alum-treated litter	NBAL	4.6	76	173	249	0	173
Triple super phosphate	NBAL	0.0	76	0	173	173	173
Normal litter	CR	1.2	24	36	190	137	173
Alum-treated litter	CR	1.5	24	54	197	119	173
Triple super phosphate	CR	0.0	24	0	173	173	173
Normal litter	3CR§	3.6	73	107	227	66	173
Alum-treated litter	3CR§	4.4	73	163	249	10	173
Triple super phosphate	3CR§	0.0	73	0	173	173	173

† NBNL, normal litter applied to supply 173 kg PAN ha^{-1}; NBAL, alum-treated litter applied to supply 173 kg PAN ha^{-1}; CR, phosphorus sources applied to supply 24 kg P ha^{-1}; 3CR, phosphorus sources applied to supply 73 kg P ha^{-1} applied once before planting in 2000.
‡ Estimated to equal 60% of organic N plus 90% of NH_3–N applied in poultry littler.
§ Treatments received P in 2000 growing season and only 173 kg N ha^{-1} as NH_3NO_3–N in 2001 and 2002.

during the 2000 growing season at Orange. Plant tissue samples were dried at 65°C, ground, and digested using a nitric acid and hydrogen peroxide digestion procedure (Jones and Case, 1990). The digests were analyzed for P and Al with atomic emissions spectroscopy using a SpectroFlame Modula Tabletop ICP–AES (Spectro Instruments, Fitchburg, MA). Tissue N concentrations were determined on ground samples with combustion and gas chromatography using a NC 2100 analyzer (CE Instruments, Lakewood, NJ).

Composite soil samples were collected to a depth of 15 cm from the study areas before initiation and from each plot at 6 and 12 mo after each treatment application. Soil samples were air-dried and ground to pass a 2-mm sieve. Samples collected before the initiation of the study were analyzed for pH (1:1 soil to water ratio) (Thomas, 1996), and extracted using the Mehlich-I dilute-double acid procedure (Kuo, 1996). Mehlich-I extracts from these initial samples were analyzed for Ca, Mg, K, and P. The pH values found in initial soil samples collected at Painter and Orange were 6.0 and 6.2, respectively. The concentrations of Ca, Mg, K, and P were 793, 102, 140, and 71 mg kg^{-1}, respectively, at Painter and 725, 143, 98, and 9 mg kg^{-1}, respectively, at Orange. Samples collected from each plot were analyzed for Mehlich-1 soil test P (M1-P) (Kuo, 1996), water-extractable phosphorus (H_2O-P) (1:10 soil to water ratio) (Kuo, 1996), exchangeable Al (1:5 soil to 1*M* KCl ratio) (Bertsch and Bloom, 1996), and pH (1:1 soil to water ratio) (Thomas, 1996).

Rainfall Simulations

Two sets of rainfall simulations were conducted in the corn experiment located at Orange. The first set of rainfall simulations were conducted in May 2003, approximately 1 yr after treatment application and incorporation. The second set of rainfall simulations were conducted in August 2003, 2 d after the application of treatments without incorporation. These treatments were applied only to evaluate runoff P concentrations shortly after application. Simulations were performed in accordance with the protocol established as part of the National Phosphorus Research Project (2001). Duplicate subplots were established within treatments which had received the following treatments: NPL, ATPL, and TSP applied at the N-based and P crop removal rates as well as the no-P control. For each set of simulations, two rainfall events were conducted on each subplot at 1-d intervals. Rainfall was applied at a rate of 70 mm h^{-1} and continued for 30 min after initiation of runoff. The weight of runoff was determined every 5 min during this 30-min period. Subsamples were taken for chemical analysis at each 5-min interval. Also, the total runoff volume collected 30 min after runoff initiation was mixed and subsampled. A portion of the subsamples were filtered through a 0.45-μm filter and acidified with HCl. Concentrations of DRP [molybdate blue (Murphy and Riley, 1962)] in filtered samples were determined. Unfiltered samples were analyzed for total P after Kjeldahl digestion with mercuric oxide and potassium sulfate catalyst (Lachat Instruments, 1995). Total C in runoff was determined on residue from 60 mL of runoff dried at 110°C with combustion and gas chromatography using a NC 2100 analyzer. Sediment was determined by the weight of residue remaining after 20 mL of runoff was dried at 110°C.

Analysis of variance, using the SAS PROC GLM procedure (SAS Institute, 2001), was used to determine significant treatment effects on measured response variables. When treatment effects were found to be significant, Fisher's protected LSD was used to separate means. Regression analyses were conducted using the SAS PROC REG procedure.

RESULTS AND DISCUSSION

Crop Response

Corn grain yields at Painter were significantly affected by treatment in 2000 and 2001 (Table 3), but were suppressed due to less favorable growing conditions (Table 4) and therefore not affected by treatments in 2002. In 2000 and 2001 at Painter, yields from treatments receiving applications of NPL and ATPL applied on an N basis (NBNL and NBAL) were significantly lower than yields from treatments receiving equivalent rates of inorganic fertilizer (Table 3). This suggests that the method used to estimate N availability overestimated PAN in the two litter sources at this location.

Concentrations of N in ear-leaves collected at mid-silk from Painter suggest that these yield reductions were due to decreased N availability before flowering. The decreased N status of corn receiving litter at the N-based rate is also apparent when comparing corn grain N concentrations, specifically in 2001 (Table 3). Jones et al. (1990) stated that concentrations of N in ear-leaves collected at mid-silk are sufficient in the range of 21 and 40 g N kg^{-1}. Nitrogen concentrations in ear-leaves collected from treatments receiving NPL or ATPL at N-based application rates were consistently below this range at Painter (Table 3). Within the N-based treatments, ear-leaf N concentrations were well correlated with grain yield during the first two years of the study at Painter (Fig. 1). The correlation between ear-leaf N and grain yield was not significant in 2002 due to suppressed yields. In 2000 and 2001, the yields from treatments receiving NH_3NO_4 as the primary PAN source (Table 2)

Table 3. Corn grain yield, ear-leaf N, ear-leaf P, and grain N concentrations at Painter, VA, in 2000–2002.

		Yield			Ear-leaf N			Ear-leaf P			Grain N		
P source	**Rate†**	**2000**	**2001**	**2002**	**2000**	**2001**	**2002**	**2000**	**2001**	**2002**	**2000**	**2001**	**2002**
		Mg ha^{-1}			g kg^{-1}								
Control	–	13.0	11.0	1.2	21.6	26.4	13.6	2.7	3.0	2.7	13.0	13.6	14.9
Normal litter	NBNL	9.9	7.5	1.4	17.9	20.3	16.6	2.3	2.7	2.9	11.5	11.9	16.8
Triple super phosphate	NBNL	12.7	10.8	1.8	20.8	25.6	20.4	2.8	3.4	3.6	12.4	12.8	16.8
Alum-treated litter	NBAL	8.7	6.1	2.1	15.9	19.9	15.6	2.0	2.5	2.4	12.1	11.0	14.7
Triple super phosphate	NBAL	12.3	10.6	2.6	23.5	25.8	20.4	2.8	3.0	3.0	12.2	12.7	16.6
Normal litter	3CR	10.9	10.0	2.1	19.3	25.2	20.8	2.4	3.1	2.9	12.3	12.6	16.7
Alum-treated litter	3CR	9.0	10.9	2.1	19.0	24.6	19.4	2.4	3.0	2.7	12.3	13.1	16.5
Triple super phosphate	3CR	12.6	11.1	2.0	23.8	26.0	20.8	3.0	3.0	3.1	12.8	12.2	16.6
	LSD (0.05)	1.5	2.2	NS	3.0	3.5	2.0	0.4	0.4	0.4	NS	1.3	1.3

† NBNL, normal litter applied to supply 173 kg plant-available N ha^{-1}; NBAL, alum-treated litter applied to supply 173 kg plant-available N ha^{-1}; CR, phosphorus sources applied to supply 24 kg P ha^{-1}; 3CR, phosphorus sources applied to supply 73 kg P ha^{-1} applied once before planting in 2000.

Table 4. Monthly rainfall totals and 60-yr rainfall averages at Painter and Orange, VA, during the 2000–2002 growing seasons.

Month	Painter 2000	Painter 2001	Painter 2002	Painter Average	Orange 2000	Orange 2001	Orange 2002	Orange Average
	mm							
April	100	60	123	78	131	18	91	78
May	112	101	57	86	55	119	49	97
June	91	134	55	86	151	213	72	94
July	211	236	145	114	87	104	132	115
August	169	52	69	105	69	76	69	101
September	122	58	53	90	130	21	63	94
Total	805	641	502	560	623	551	476	578

were as much as 4.2 Mg ha^{-1} higher than the estimated yield of 8.8 Mg ha^{-1}, whereas yields from those treatments receiving all or most of the PAN as poultry litter were equivalent to or below 8.8 Mg ha^{-1} at Painter due to an overestimation of PAN at the Painter location for both sources of poultry litter. The data demonstrate the importance of using tools such as the pre-side dress nitrate test (Evanylo and Alley, 1998) to evaluate mid-season soil N status of corn fertilized with poultry litter. Although not significant, the ear-leaf N concentrations in the treatment receiving ATPL at the N-based rate were consistently lower than those found in the treatment receiving NPL at the N-based rate during each year of the study (Table 3), further suggesting decreased N availability and an overestimation of PAN in treatments receiving ATPL compared to NPL. These consistent yet nonsignificant results could imply a minor difference in the availability of N found in the two litter sources, which would be inconsistent with previous research. Gilmour et al. (2004) recently conducted laboratory incubations to evaluate the effects of alum treatment on the decomposition and N mineralization rates of poultry litter and found no significant differences in the N mineralization rates of ATPL and NPL. Unlike conditions for this laboratory study, field conditions at Painter were likely not optimum for N mineralization as can be seen from the reduced yields produced by both litter sources applied on an N basis compared to inorganic fertilizer. These suboptimum conditions could have magnified any differences among mineralization rates of the two litters.

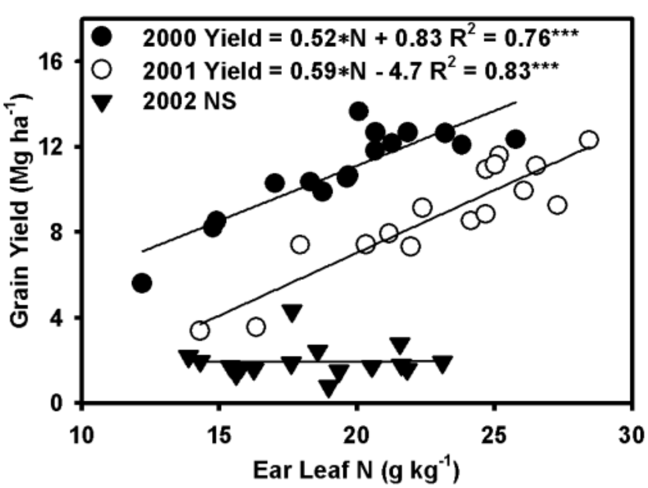

Fig. 1. The relationship between ear-leaf N content and grain yield for the N-based treatments at Painter, VA. *** Significant at the 0.001 probability level; NS, regression not significant.

In addition to the N-based application rates, applications of NPL and ATPL at the 3CR P rate at the Painter site in 2000 resulted in significantly lower yields than an equivalent application of inorganic fertilizer (Table 3). Also, for the 3CR P rate in 2000 the yield from the NPL source was significantly greater than yields from ATPL. At the 3CR P rate the ATPL treatment received all but 10 kg PAN ha^{-1} as ATPL whereas the NPL treatment received an additional 66 kg PAN ha^{-1} as NH_4NO_3 (Table 2). This supplemental N applied as NH_4NO_3 contributed to the increased yield response to the NPL applied at the 3CR P rate compared to the equivalent ATPL treatment. These differences at the 3CR P rate did not persist in 2001 and 2002 because these treatments received NH_4NO_3 as the sole N source and no additional poultry litter. Also, ear-leaves collected during the 2000 crop year from treatments receiving NPL or ATPL at the 3CR P rate had 19 and 20% lower N concentrations, respectively, than ear-leaves collected from treatments receiving equivalent rates of inorganic fertilizer (Table 3). This response in ear-leaf N concentration was similar to that found in grain yield. Again both the ear-leaf N and grain yield data from the 3CR P rate in 2000 suggests that PAN was overestimated at the Painter location as was found in the N-based rates.

No significant differences in grain yield or tissue N were found at Painter among sources applied at the CR rate. The average yields for the CR P rate at Painter were 12.4, 10.9, and 2.4 Mg ha^{-1} in 2000, 2001, and 2002, respectively. The NPL and ATPL sources applied at the CR rate supplied 21 and 31% of the PAN applied to these plots, with the remaining PAN applied as NH_4NO_3. This combination of litter and supplemental inorganic N was adequate to produce yields similar to those treatments receiving only inorganic fertilizer.

The concentrations of ear-leaf P follow a similar trend as that found in ear-leaf N concentrations at Painter (Table 3). At the N-based P application rates, ear-leaf P concentrations were consistently lower in treatments receiving either ATPL or NPL compared to treatments receiving TSP. Also, in ear-leaves collected in 2000 the P concentrations were reduced in treatments receiving either ATPL or NPL at the 3CR P rate compared to those found in ear-leaves collected from the treatment receiving the equivalent rate of P as TSP. The lack of significant differences between the control treatment which received no P and the TSP treatments shows that the site was unresponsive to additional P. Therefore the suppressed ear-leaf P concentrations found in the litter treatments are more likely due to interactions between N availability and P uptake.

Because no response in tissue N concentration to the N availability among sources was observed at the CR P rate, this P rate can be used to investigate differences in P availability among the P sources. At Painter no significant differences in the ear-leaf P concentrations were found among treatments receiving the three P sources at the CR P rate (data not shown), nor were these ear-leaf P concentrations different from those found in the check treatment. This demonstrates a lack of crop response to CR rates of P additions at Painter.

Our results from Orange are similar to those found by Gilmour et al. (2004) in that there were no apparent yield responses due to difference in N availability among sources. No significant ($p < 0.05$) treatment by year interactions were observed in grain yield and on combining yield data over years no significant treatment effects were observed (Table 5). Before the initiation of this study at Orange, the M1-P level was 7 mg P kg^{-1}. At this level of M1-P the Virginia Tech Soil Testing Laboratory recommends a fertilizer application of 39 kg P ha^{-1} (Donohue, and Heckendorn, 1994), yet no grain yield response to P fertilizer applications of as high as 116 kg P ha^{-1} (P application resulting from the NBNL rate) were observed at Orange.

At Orange there were no significant year by treatment interactions ($p < 0.05$) for ear-leaf P or N content, or for grain N or P content; therefore, ear-leaf and grain N and P concentration data were combined over years (Table 5). No significant differences, due to treatment, in ear-leaf N or P concentrations were found at Orange. The ear-leaf N and P concentrations found at Orange were well within the sufficiency range presented by Jones et al. (1990) and demonstrate a lack of mid-season response to pre-plant P and N fertilizer application. There were also no significant differences in grain N concentrations among treatments. However, when the concentration of grain P is averaged for each treatment across years there were significant treatment effects. Specifically, the rate of application significantly affected the concentration of P in the grain with no significant differences among sources at any rate. Averaged over the 3-yr study at Orange the N-based treatment applications resulted in a grain P concentration of 2.8 g P kg^{-1}, which was significantly greater [$LSD_{(0.05)} = 0.3$] than concentrations resulting from the check, and the CR P application rate, and 3CR P application rate which resulted in average concentrations of 2.5, 2.5, and 2.6 g P kg^{-1}, respectively (Table 5). The lack of differences in corn grain P concentrations among the three sources confirms previous research evaluating crop P uptake from ATPL-treated soils which found only minor differences in tissue P concentrations between treatments fertilized with ATPL and NPL. Shreve et al. (1995) evaluated nutritional composition of fescue receiving non-amended litter and litter treated with alum (1:5 amendment to litter ratio) at a rate of 11.2 Mg ha^{-1}. They found that P concentrations in harvested fescue forage receiving ATPL were lower at 6.5 g P kg^{-1}, but not significantly lower than fescue receiving NPL, which contained 7.3 g P kg^{-1}. This decline in tissue P was attributed to a dilution of P due to increased plant growth from the ATPL treatment.

Table 5. Average P and N content of corn ear-leaves collected during mid-silk in 2001 and 2002 and grain harvested in 2000–2002 at Orange, VA.

			Ear-leaves		Grain	
P source	**Rate†**	**Yield**	**P**	**N**	**P**	**N**
		Mg ha^{-1}	g kg^{-1}			
Control	–	8.2	2.5	25.5	2.5	13.8
Normal litter	NBNL	8.0	2.5	25.2	2.8	14.0
Triple superphosphate	NBNL	7.9	2.6	25.7	2.7	14.0
Alum-treated litter	NBAL	7.8	2.4	25.2	2.8	13.9
Triple superphosphate	NBAL	8.3	2.6	26.7	2.7	14.0
Normal litter	CR	7.8	2.5	26.2	2.6	13.9
Alum-treated litter	CR	7.6	2.5	26.5	2.6	13.9
Triple superphosphate	CR	7.7	2.6	26.6	2.5	14.0
Normal litter	3CR	7.8	2.4	25.9	2.5	13.9
Alum-treated litter	3CR	8.2	2.4	25.7	2.4	13.7
Triple superphosphate	3CR	8.1	2.6	26.1	2.5	14.0
	LSD (0.05)	NS	NS	NS	0.3	NS

† NBNL, normal litter applied to supply 173 kg plant-available N ha^{-1}; NBAL, alum-treated litter applied to supply 173 kg plant-available N ha^{-1}; CR, phosphorus sources applied to supply 24 kg P ha^{-1}; 3CR, phosphorus sources applied to supply 73 kg P ha^{-1} applied once before planting in 2000.

Aluminum Availability

The addition of ATPL did not result in significant treatment by year interactions nor were there significant treatment effects on corn grain or ear-leaf Al concentrations ($p < 0.05$). The average corn grain Al concentrations being similar at both locations were 25.8 and 28.3 mg Al kg^{-1} at Painter and Orange, respectively. In contrast, the average ear-leaf Al concentration at Painter was nearly three times greater at 88 mg Al kg^{-1} than that found at Orange, which averaged 33 mg Al kg^{-1}. Despite this difference, ear-leaf Al concentrations at both locations were well within the expected normal ranges of 10 to 200 mg Al kg^{-1} suggested by Jones et al. (1990). The lack of significant differences in tissue Al concentrations among sources is inconsistent with the findings of Shreve et al. (1995) who reported significantly higher Al concentrations in tall fescue treated with ATPL (91 g Al kg^{-1}) compared to that found in tall fescue forage treated with NPL (48 g Al kg^{-1}).

Although no differences in tissue Al concentrations were found, there were significant treatment differences in soil pH and exchangeable soil Al concentration. At Painter the N-based applications of ATPL and NPL resulted in significantly elevated pH levels and subsequently lower exchangeable Al concentrations compared to treatments receiving equivalent applications of commercial fertilizer (Table 6). These results are consistent with findings of Kingery et al. (1994) who found that long-term applications of poultry litter to pastures resulted in increased soil pH. Moore et al. (1999) discussed findings from field studies conducted in Arkansas, in which they found that the pH values of soils

Table 6. Soil pH and exchangeable Al in soil collected in the fall of 2002 at Painter and Orange, VA.

		Painter		Orange	
P source	Rate†	pH	Al	pH	Al
			mg kg^{-1}		mg kg^{-1}
Control	–	5.57	0.94	6.08	1.47
Normal litter	NBNL	5.92	0.08	6.54	0.56
Triple superphosphate	NBNL	5.66	0.76	5.99	1.74
Alum-treated litter	NBAL	5.81	0.62	6.19	0.73
Triple superphosphate	NBAL	5.44	3.08	6.05	1.33
Normal litter	CR	5.53	1.20	6.22	0.78
Alum-treated litter	CR	5.57	2.72	6.11	1.05
Triple superphosphate	CR	5.52	2.14	6.16	1.37
Normal litter	3CR	5.72	0.45	6.28	0.94
Alum-treated litter	3CR	5.62	0.85	6.06	1.75
Triple superphosphate	3CR	5.54	4.09	6.07	1.72
	LSD (0.05)	0.24	NS	0.20	0.62

† NBNL, normal litter applied to supply 173 kg plant-available N ha^{-1}; NBAL, alum-treated litter applied to supply 173 kg plant-available N ha^{-1}; CR, phosphorus sources applied to supply 24 kg P ha^{-1}; 3CR, phosphorus sources applied to supply 73 kg P ha^{-1} applied once before planting in 2000.

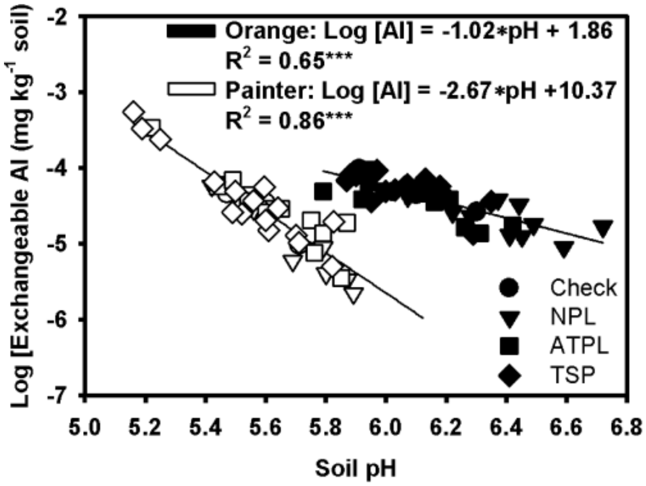

Fig. 2. Exchangeable soil Al as a function of soil pH in soils collected at Painter, VA, and Orange, VA, in the fall of 2002. *** Significant at the 0.001 probability level.

receiving either NPL or ATPL were elevated compared to those receiving ammonium nitrate (NH_4NO_3). At Orange the N-based applications of NPL again resulted in significantly higher soil pH and decreased exchangeable Al compared to the treatment receiving equivalent rates of commercial fertilizer. Application of ATPL at the N-based rate did not elevate pH at Orange compared to equivalent applications of commercial fertilizer. This lack of increased soil pH could be a result of lower rates of litter application associated with the ATPL compared to NPL (Table 2). Also, the acidity of the alum added to the litter would have been neutralized by carbonates and other bases present in the litter. Because of this acid neutralization the carbonate equivalent of the ATPL is likely lower than that of NPL. These two factors, along with the increased buffer capacity of the Davidson soil compared to the Bojac soil, did not allow the ATPL to increase soil pH as was found at Painter. At Orange, the pH and Al concentrations in treatments receiving ATPL at the 3CR rate more closely resembled those treatments receiving TSP at the equivalent rate.

Given the variations in soil pH and exchangeable Al associated with treatment, it is important to evaluate the effect of applying ATPL on the relationship between pH and the Al concentration in these soils. The relationships between pH and exchangeable Al concentration across P sources at Painter and Orange are illustrated in Fig. 2. Alum-treated poultry litter had no effect on the slope or intercept of the line representing this relationship at either location. These findings show that although ATPL may not be as effective in maintaining soil pH compared to NPL, it did not affect exchangeable Al concentrations at a given soil pH.

Soil Phosphorus Status

Significant changes in M1-P were observed at both locations in soil samples collected in the fall of 2002 (Table 7). At Painter, M1-P in treatments receiving annual applications of ATPL at the NBAL rate was 37% lower than those receiving NPL at the NBNL rate while at Orange, this reduction was 32%. Some of these differences in M1-P concentrations may be a result of differences in the net P application rates resulting from N-based applications of the two litter sources (Table 7). However, this data can be used to show that each kg of net P applied per ha in ATPL results in a lower increase in the M1-P concentration compared to the two other sources. For example, when the difference in M1-P concentrations found in the control and the treatment receiving ATPL at the NBAL rate is divided by the difference in the net P applied to these two treatments it is found that the M1-P concentration increases by 0.09 mg P kg^{-1} for each kg of net P applied ha^{-1} at the Painter location. However, when this ratio is calculated for the NPL or TSP applied at the N-based rates at Painter the M1-P concentration increases by approximately 0.2 mg P kg^{-1} for each kg of net P applied ha^{-1}. These results suggest that using ATPL can result in lower M1-P levels even when net P additions are equal to or greater than additions of TSP or NPL. The total P applied to the CR and 3CR P treatments was nearly equal to the total P removed from these treatments at Painter (Table 7). At Orange the net P addition for these treatments ranged from 9 to 19 kg P ha^{-1}. As a result, minimal changes in M1-P concentrations were observed. In fact, the application of TSP at the CR P rate at Painter was the only CR treatment at either location to result in M1-P concentrations significantly greater than the control (Table 7).

Soil concentrations of H_2O-P in the fall of 2002 followed trends similar to changes in M1-P (Table 7). Neither the CR nor the 3CR P rates, irrespective of source, resulted in significant increases in H_2O-P concentrations compared to the no P control treatment. Applications of ATPL at the NBAL rate resulted in 54 and 56% lower H_2O-P concentrations than the application of NPL at the NBNL rates at Painter and Orange, respectively. Moore et al. (1999) showed only a minor, nonsignificant difference in the H_2O-P content of soils receiving 169 kg P ha^{-1} as ATPL when

Table 7. Total P applied and removed and the resulting net P addition for each treatment during the 3-yr studies conducted at Painter and Orange, VA, and the resulting Mehlich 1–extractable soil phosphorus (M1-P) and water-extractable phosphorus (H_2O-P) found in soils collected in the fall of 2002.

			Painter				Orange			
P source	Rate†	Total P applied	Total P removed	Net P addition	M1-P	H_2O-P	Total P removed	Net P addition	M1-P	H_2O-P
			kg ha^{-1}		mg kg^{-1}		kg ha^{-1}		mg kg^{-1}	
Control	–	0	74	−74	71	2.5	60	−60	8	0.2
Normal litter	NBNL	348	56	292	147	13.0	65	283	22	0.6
Triple superphosphate	NBNL	348	71	277	150	11.6	63	285	28	0.5
Alum-treated litter	NBAL	228	49	179	93	6.0	64	164	15	0.3
Triple superphosphate	NBAL	228	76	152	115	5.6	66	162	20	0.3
Normal litter	CR	73	80	−7	76	4.1	57	17	8	0.2
Alum-treated litter	CR	73	69	4	70	3.4	55	19	8	0.2
Triple superphosphate	CR	73	81	−8	94	4.6	57	16	12	0.2
Normal litter	3CR	73	66	7	82	5.1	60	13	9	0.2
Alum-treated litter	3CR	73	69	4	86	4.8	65	9	10	0.2
Triple superphosphate	3CR	73	76	−3	80	4.3	59	14	10	0.2
	LSD (0.05)		11	11	21	2.6	6	6	6	0.2

† NBNL, normal litter applied to supply 173 kg plant-available N ha^{-1}; NBAL, alum-treated litter applied to supply 173 kg plant-available N ha^{-1}; CR, phosphorus sources applied to supply 24 kg P ha^{-1}; 3CR, phosphorus sources applied to supply 73 kg P ha^{-1} applied once before planting in 2000.

compared to the check, yet found a fourfold increase in H_2O-P in soil receiving 201 kg P ha^{-1} as NPL when applied for 3 yr to tall fescue. Their findings are similar to ours but lack TSP treatments for comparisons. In contrast to the trends found in M1-P, there was no difference in H_2O-P concentrations between treatments receiving TSP or ATPL at the NBAL rate (Table 7). These data suggest that although the ATPL additions result in less labile solid-phase P as compared to TSP, the addition of Al to the soil in the ATPL is not sufficient to decrease the solution-phase P solubility in these soils to a level significantly below that found in treatments receiving equivalent rates of TSP. This lack of significant difference in the H_2O-P concentrations between treatments receiving ATPL and TSP, specifically at the NBAL rate, may be explained by the lower pH and subsequently higher exchangeable Al concentrations in the TSP treatment (Table 6). This effect of pH on the H_2O-P concentrations was most prominent at the Painter location where no significant difference was found between ATPL and TSP applied on an N basis although both treatments resulted in H_2O-P concentrations that were higher than the no-P control. The same pH effect could also explain the decreased solubility of P in treatments receiving TSP at the NBNL rate compared to treatments receiving NPL at the NBNL rate.

Phosphorus Loss in Simulated Runoff

Due to the lack of significant differences and variability in the volume of runoff loss from the small plots used in this study runoff data are presented as concentrations. Although DRP concentrations were low in the first and second rainfall events, which were conducted in May 2003 before a fourth P application, significant differences were found among treatments (Table 8). Treatments that had received 3 yr of the N-based applications of all three P sources resulted in significantly higher runoff DRP during the first events as compared to the control treatment. During the second event only, the N-based treatments receiving NPL and TSP resulted in DRP concentrations significantly greater than the control. Alum-treated poultry litter applied at the NBAL rate resulted in the lowest DRP concentrations in runoff, during the first and second events, when compared to the other two sources of P applied on an N basis (Table 8). This is a result of the lower M1-P concentrations found in treatments receiving ATPL applied on an N basis as compared to those receiving TSP or NPL (Table 7). The DRP concentrations found in runoff from both events were well related with M1-P, with no significant differences in the slope or intercept of the relationships found during the two rainfall events (Fig. 3). There were no significant differences in runoff total P concentrations among treatments during the first and second events (Table 8).

Dissolved reactive P and total P concentrations in runoff from treatments that received P applications 2 d before the set rainfall events are shown as the third and fourth runoff events in Table 8. The concentrations of DRP and total P in runoff from each of these rainfall events were significantly affected by treatment (Table 8). The ATPL applied at the NBAL rate resulted in 61% less DRP in runoff during the first event following application compared to the NPL applied at the NBNL rate. Lower DRP can be attributed to the decreased P solubility in ATPL. Although soluble P was not measured on litter used in this study, previous work has shown that the amendment of poultry litter with alum reduces water-soluble P in litter on average by 73% when treated to produce litter with Al to P ratios of 0.57 (Sims and Luka-McCafferty, 2002). The litters used in our study were collected from poultry production facilities included in the study presented by Sims and Luka-McCafferty (2002) and the ATPL has a Al to P ratio of 0.51, therefore it likely has very similar soluble P concentrations. Evidence of the effect of decreased P solubility in the ATPL is found when DRP concentrations in runoff from plots receiving ATPL and TSP applied at the NBAL rate are compared. At this rate, DRP concentrations were 48% lower in runoff during the third event from the ATPL treatments compared to TSP treatments. The effect of the lower P solubility in ATPL is also evident when comparing DRP

Table 8. Effect of P source, application rate, and timing of runoff event after P application on P loss, sediment loss, and total carbon loss in runoff collected at Orange, VA, during simulated rainfall.

P source	Rate†	DRP‡	Total P	Sediment	Total carbon
		mg L^{-1}		g L^{-1}	mg L^{-1}
	First runoff event, May 2003 (treatments applied and incorporated approximately 1 yr previous)				
Control	–	0.01	2.0	3.3	NA§
Normal litter	NBNL	0.06	1.9	1.4	NA
Triple superphosphate	NBNL	0.05	5.1	14.8	NA
Alum-treated litter	NBAL	0.04	4.6	7.5	NA
Triple superphosphate	NBAL	0.06	3.5	11.5	NA
Normal litter	CR	0.02	5.7	13.3	NA
Alum-treated litter	CR	0.03	2.2	2.1	NA
Triple superphosphate	CR	0.02	3.2	3.6	NA
	LSD (0.05)	0.01	NS	NS	
	Second runoff event, May 2003 (treatments applied and incorporated approximately 1 yr previous)				
Control	–	0.02	3.2	4.8	NA
Normal litter	NBNL	0.06	2.3	1.9	NA
Triple superphosphate	NBNL	0.06	5.1	12.2	NA
Alum-treated litter	NBAL	0.04	3.9	4.0	NA
Triple superphosphate	NBAL	0.06	5.7	9.8	NA
Normal litter	CR	0.02	4.8	10.6	NA
Alum-treated litter	CR	0.03	2.8	2.6	NA
Triple superphosphate	CR	0.02	3.7	5.4	NA
	LSD (0.05)	0.02	NS	NS	
	Third runoff event, August 2003 (treatments were applied without incorporation 2 d previous)				
Control	–	0.0	0.9	1.4	22
Normal litter	NBNL	78.0	103.7	2.3	620
Triple superphosphate	NBNL	73.2	73.5	2.6	30
Alum-treated litter	NBAL	30.5	96.3	3.5	906
Triple superphosphate	NBAL	53.1	58.4	1.3	38
Normal litter	CR	19.7	24.6	2.3	227
Alum-treated litter	CR	5.7	16.8	1.0	141
Triple super phosphate	CR	10.3	15.8	2.5	41
	LSD (0.05)	4.5	13.7	1.4	54
	Fourth runoff event, August 2003 (treatments were applied without incorporation 3 d previous)				
Control	–	0.0	0.9	1.2	18
Normal litter	NBNL	6.4	9.5	0.6	76
Triple superphosphate	NBNL	2.2	14.1	3.0	53
Alum-treated litter	NBAL	1.0	5.7	1.0	79
Triple superphosphate	NBAL	4.4	8.4	1.9	30
Normal litter	CR	0.7	2.8	1.3	33
Alum-treated litter	CR	0.3	1.5	0.6	25
Triple superphosphate	CR	0.3	3.6	2.8	37
	LSD (0.05)	0.6	8.2	NS	NS

† NBNL, normal litter applied to supply 173 kg plant-available N ha^{-1}; NBAL, alum-treated litter applied to supply 173 kg plant-available N ha^{-1}; CR, phosphorus sources applied to supply 24 kg P ha^{-1}; 3CR, phosphorus sources applied to supply 73 kg P ha^{-1} applied once before planting in 2000.
‡ Dissolved reactive phosphorus.
§ Not analyzed; total carbon was not determined for runoff collected in the first and second runoff events.

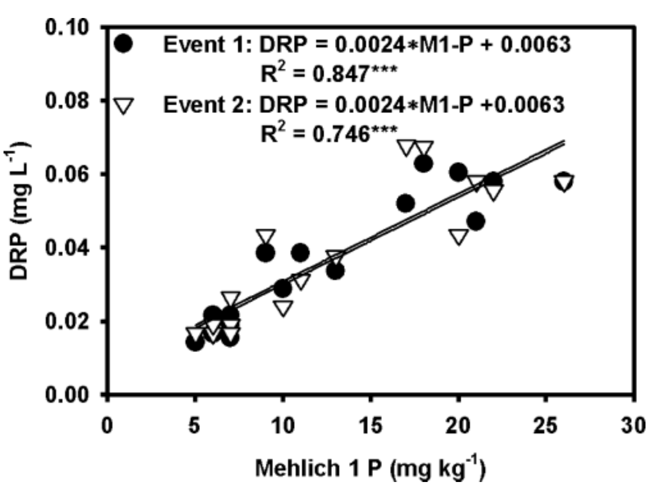

Fig. 3. Relationship between the dissolved reactive phosphorus (DRP) found in runoff collected from two rainfall events conducted before treatment applications and Mehlich 1–extractable soil phosphorus (M1-P). * Significant at the 0.001 probability level.**

concentrations found in runoff from treatments receiving CR rates of the three sources. At this rate, DRP from treatments receiving ATPL was 71 and 45% lower as compared to runoff from NPL and TSP treatments, respectively (Table 8).

The runoff total P concentrations were generally higher for treatments receiving either NPL or ATPL compared to treatments receiving TSP during the third event (Table 8). This is especially evident at both N-based rates. In the N-based treatments, the DRP concentrations from treatments receiving TSP were nearly equal to the total P concentrations. In runoff from treatments receiving NPL at the NBNL rate, DRP accounted for 75% of the total P, whereas DRP from treatments receiving ATPL at the NBAL rate accounted for only 32% of the total P in runoff. Therefore, although litter applications resulted in greater total P losses, less of this P was in a soluble form as compared to TSP. The lack of a significant difference in total P concentrations between NPL and ATPL is contradictory to previous research where applications of ATPL to fescue pastures resulted in 65% lower total P in runoff than from fescue receiving non-amended litter applied on an equal weight basis (Moore et al., 2000). The row crop system evaluated in our study likely allowed for greater potential erosion and litter particle losses compared to the previous study conducted on fescue pasture. Therefore total C in runoff was determined for use as an indicator of litter particle concentrations in runoff. Assuming the amount of total C in runoff gives an indication of the amount of litter particles lost in runoff, a substantially greater concentration of litter particles was present in the third runoff event from the treatment receiving ATPL at the NBAL rate compared to the treatment receiving NPL at the NBNL rate (Table 8). This is dissimilar to results from Moore et al. (1998) which showed decreased soluble organic C in runoff from fescue treated with ATPL as compared to treatments receiving NPL. The decrease in the concentrations of soluble organic C found by Moore et al. (1998) may be attributed to changes in the chemical character of litter treated with alum. However, the differences in the concentration of total C found among treatments in our study are likely due to physical differences between the two litter sources or differences in the hydrology of the plots. Evidence of a hydrological effect is found when inconsistencies between the N-based treatments and the CR treatments are compared. Application of ATPL at the CR rate resulted in a 38% lower total C concentration as compared to NPL, whereas at the N-based rate the ATPL resulted in a 32% greater total C concentration. Despite these inconsistencies the evaluation of total C concentrations in runoff helped to assess the resulting trends among total P concentrations. Specifically the lack of an expected significant difference in total P runoff concentrations among treatments receiving ATPL and NPL on an N basis is due to elevated litter particle concentrations in runoff from the ATPL (NBAL) treatment even though the amount of total P applied was 34% less than that applied to the NPL (NBNL) treatment. These results are similar to those found by Penn et al. (2004) who also found that total P losses are more a function of the amount of manure particles lost in runoff than of P application rates. The data highlight an important limitation in using small subplots to evaluate P loss in runoff. Specifically, that differences in hydrology of small runoff plots can have significant impacts on the results.

CONCLUSIONS

As a nutrient source for corn grain production, ATPL performed similarly to NPL. Data collected at Painter confirmed the importance of mid-season evaluations of the N status of corn when using poultry litter as the primary N source. The use of ATPL did not appear to affect the concentration of P in corn ear-leaves or grain, even at Orange where soil test P levels (M1-P) were below the optimum range at the initiation of the study. Aluminum concentrations in corn ear-leaves and grain were not increased in treatments receiving ATPL nor were the exchangeable Al concentrations in soils receiving ATPL increased. In fact, exchangeable Al concentrations were elevated only in treatments receiving NH_4NO_3 as the primary N source. At the N-based application rates, both M1-P and H_2O-P were lower in treatments receiving ATPL compared to NPL. Much of this reduction could be attributed to lower rates of total and net P applications in the ATPL treatments (Table 8). Through comparison to inorganic fertilizer treatments, additional reductions in M1-P concentrations could be attributed to the alum present in the litter. These reductions in M1-P concentrations resulted in decreased DRP losses in simulated runoff from soils one year after the third-annual treatment applications. The most beneficial effect of litter treatment with alum was the reduction in DRP loss in runoff when rainfall occurred shortly after application. However, applications of ATPL did not result in consistently lower total P concentrations in runoff because of the apparent loss of litter particles when using small runoff plots in this cultivated row-cropping system. Inconsistencies in the amount of litter particles lost from the runoff plots were a result of shortcomings of the small simulated runoff plot method employed to determine runoff losses. The results point out that when using small runoff plots small-scale variations in hydrology can significantly impact simulation results. Therefore, although small-scale simulations are useful in comparing specific treatments, care should be taken when extrapolating the data to edge of field losses especially when evaluating systems shortly after litter application.

The experimental design employed in this study was useful in comparing environmental and production responses resulting from ATPL, NPL, or TSP applied at "agronomic rates" as specified by local regulations mandated by Virginia House Bill 1207. These comparisons at agronomic rates are important because much of the litter is now applied at these rates as mandated by government agencies. Previous research has focused on comparing ATPL to NPL when applied on an equal dry weight basis or at equal total P rates. The inclusion of rates determined by the estimated PAN content of litter allowed us to evaluate ATPL as a nutrient source and to evaluate the effectiveness of current regulations in meeting crop production and environmental goals. Our study demonstrated inaccuracies in our current method of estimating PAN from both ATPL and NPL, which prompts interest in the reevaluation of these estimates, and highlighted the importance of in-season evaluations of the N status of the crop when using litter as the primary N source. However, the design of our experiment did not allow for direct comparisons of N availability between NPL and ATPL due to slightly different total N application rates for the two litters. Further research should focus on evaluating any differences in N mineralization rates between NPL and ATPL. Also, the addition of alum not only affects the availability of P in litter but may also reduce the liming value of the litter, and consequently lower soil pH and P solubility in soil. Therefore, interactions among these factors should be considered in the design of future research studies.

In conclusion, the results of this study show that the use of ATPL can reduce runoff P and soil test P when using poultry litter as a nutrient source for corn production without significant changes in production management strategies.

REFERENCES

Bertsch, P.M., and P.R. Bloom. 1996. Aluminum. p. 517–550. *In* D.L. Sparks (ed.) Methods of soil analysis. Part 3. SSSA Book Ser. 5. SSSA, Madison, WI.

Brosius, M.R., M.A. Beck, L.W. Zelazny, W.L. Daniels, G.L. Mullins, J.W. Pease, and M.L. Wolfe. 2000. Phosphorus mobility on agricultural lands of Virginia: Annual report. Virginia Dep. of Conserv. and Recreation, Div. of Soil and Water Conserv., Richmond.

Donohue, S.J. 2000. Soil testing and plant analysis. p. 75–86. *In* Agronomy handbook. Publ. 424-100. Virginia Coop. Ext., Blacksburg.

Donohue, S.J., and S.E. Heckendorn. 1994. Soil test recommendations for Virginia. Virginia Coop. Ext. Publ., Blacksburg.

Edwards, D.R., and T.C. Daniel. 1993. Effects of poultry litter application rate and rainfall intensity on quality of runoff from fescuegrass plots. J. Environ. Qual. 22:361–365.

Evanylo, G.K., and M.M. Alley. 1998. Nitrogen soil testing for corn in Virginia. Publ. 418-016. Virginia Coop. Ext., Blacksburg.

Evanylo, G.K., and G.L. Mullins. 2000. Utilization of organic wastes as nutrient sources and soil amendments. p. 99–109. *In* Agronomy handbook. Publ. 424-100. Virginia Coop. Ext., Blacksburg.

Gilmour, J.T., M.A. Koehler, M.L. Cabrera, L. Szajdak, and P.A. Moore, Jr. 2004. Alum treatment of poultry litter: Decomposition and nitrogen dynamics. J. Environ. Qual. 33:402–405.

Jones, J.B., Jr., and V.W. Case. 1990. Sampling, handling, and analyzing plant tissue samples. p. 389–427. *In* R.L. Westerman (ed.) Soil testing and plant analysis. 3rd ed. SSSA Book Ser. 3. SSSA, Madison, WI.

Jones, J.B., Jr., H.V. Eck, and R. Voss. 1990. Plant analysis as an aid in fertilizing corn and grain sorghum. p. 521–547. *In* R.L. Westerman (ed.) Soil testing and plant analysis. 3rd ed. SSSA Book Ser. 3. SSSA, Madison, WI.

Kingery, W.L., C.W. Wood, D.P. Delaney, J.C. Williams, and G.L. Mullins. 1994. Impact of long-term land application of broiler litter on environmentally related soil properties. J. Environ. Qual. 23: 139–147.

Kuo, S. 1996. Phosphorus. p. 869–919. *In* D.L. Sparks (ed.) Methods of soil analysis. Part 3. SSSA Book Ser. 5. SSSA, Madison, WI.

Lachat Instruments. 1995. Total phosphorus in Kjeldahl digests. QuikChem Method 10-115-01-1-C. Lachat Instruments, Milwaukee, WI.

Miles, D.M., P.A. Moore, Jr., D.R. Smith, D.W. Rice, H.L. Stilborn, D.R. Rowe, B.D. Lott, S.L. Branton, and J.D. Simmons. 2003. Total and water-soluble phosphorus in broiler litter over three flocks with alum litter treatment and dietary inclusion of high available phosphorus corn and phytase supplementation. Poult. Sci. 82: 1544–1549.

Moore, P.A., Jr., T.C. Daniel, and D.R. Edwards. 1999. Reducing phosphorus runoff and improving poultry production with alum. Poult. Sci. 78:692–698.

Moore, P.A., Jr., T.C. Daniel, and D.R. Edwards. 2000. Reducing phosphorus runoff and inhibiting ammonia loss from poultry manure with aluminum sulfate. J. Environ. Qual. 29:37–49.

Moore, P.A., Jr., T.C. Daniel, D.R. Edwards, and D.M. Miller. 1995. Effect of chemical amendments on ammonia volatilization from poultry litter. J. Environ. Qual. 24:293–300.

Moore, P.A., Jr., T.C. Daniel, J.T. Gilmour, B.R. Shreve, D.R. Edwards, and B.H. Wood. 1998. Decreasing metal runoff from poultry litter with aluminum sulfate. J. Environ. Qual. 27:92–99.

Moore, P.A., Jr., and D.M. Miller. 1994. Decreasing phosphorus solubility in poultry litter with aluminum, calcium, and iron amendments. J. Environ. Qual. 23:325–330.

Murphy, J., and J.P. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chim. Acta 27:31–36.

National Phosphorus Research Project. 2001. National research project for simulated rainfall - surface runoff studies: Protocol. Available at http://ars.usda.gov/Main/site_main.htm?docid=2382 (verified 23 Sept. 2005). North Carolina State Univ., Raleigh.

Nichols, D.J., T.C. Daniel, P.A. Moore, Jr., D.R. Edwards, and D.H. Pote. 1997. Runoff of estrogen hormone 17β-estradiol from poultry litter applied to pasture. J. Environ. Qual. 26:1002–1006.

Peak, D., J.T. Sims, and D.L. Sparks. 2002. Solid-state speciation of natural and alum-amended poultry litter using XANES spectroscopy. Environ. Sci. Technol. 36:4253–4261.

Penn, C.J., G.L. Mullins, L.W. Zelazny, J.G. Warren, and J.M. McGrath. 2004. Surface runoff losses of phosphorus from Virginia soils amended with turkey manure using phytase and high available phosphorus corn diets. J. Environ. Qual. 33:1431–1439.

Pote, D.H., T.C. Daniel, A.N. Sharpley, P.A. Moore, Jr., D.R. Edwards, and D.J. Nichols. 1996. Relating extractable soil phosphorus losses in runoff. Soil Sci. Soc. Am. J. 60:855–859.

SAS Institute. 2001. The SAS system for Windows: Version 8.02. SAS Inst., Cary, NC.

Sharpley, A.N. 1995. Dependence of runoff phosphorus on extractable soil phosphorus. J. Environ. Qual. 24:920–926.

Sharpley, A.N., S.J. Smith, and W.R. Bain. 1993. Nitrogen and phosphorus fate from long-term poultry litter applications to Oklahoma soils. Soil Sci. Soc. Am. J. 57:1131–1137.

Sharpley, A.N., S.J. Smith, O.R. Jones, W.A. Berg, and G.A. Coleman. 1992. The transport of bioavailable phosphorus in agricultural runoff. J. Environ. Qual. 21:30–35.

Shreve, B.R., P.A. Moore, Jr., T.C. Daniel, D.R. Edwards, and D.M. Miller. 1995. Reduction of phosphorus in runoff from field-applied poultry litter using chemical amendments. J. Environ. Qual. 24: 106–111.

Shreve, B.R., P.A. Moore, Jr., D.M. Miller, T.C. Daniel, and D.R. Edwards. 1996. Long-term phosphorus solubility in soils receiving poultry litter treated with aluminum, calcium, and iron amendments. Commun. Soil Sci. Plant Anal. 27:2493–2510.

Simpson, T.W. 1998. A citizen's guide to the Water Quality Improvement Act of 1998. Available at http://www.agnr.umd.edu/waterquality/citizWQ.html (verified 31 Aug. 2005). Univ. of Maryland Coop. Ext., College Park.

Sims, J.T. 1999. Delaware's state nutrient management program: Overview of the 1999 Delaware Nutrient Management Act. Publ. NM-01. College of Agric. and Natural Resour., Univ. of Delaware, Newark.

Sims, J.T., and N.J. Luka-McCafferty. 2002. On-farm evaluation of aluminum sulfate (alum) as a poultry litter amendment: Effects on litter properties. J. Environ. Qual. 31:2066–2073.

Thomas, G.W. 1996. Soil pH and soil acidity. p. 475–490. *In* D.L. Sparks (ed.) Methods of soil analysis. Part 3. SSSA Book Ser. 5. SSSA, Madison, WI.

Virginia Department of Conservation and Recreation. 1995. Virginia nutrient management standards and criteria. Available at http://www.dcr.virginia.gov/sw/docs/ntmgtstds.pdf (verified 31 Aug. 2005). VDCR, Richmond.